Development of ARES Cavity Simulator

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Abstract

For the SuperKEKB project, a new LLRF control system has been developed to realize high accuracy and flexibility. Accordingly the evaluation of the new LLRF system carries significant weight. For the test operation in quantity production of new LLRF systems, an ARES cavity simulator was developed. The ARES is a special normal conducting cavity for the KEKB, which has a unique structure in order to avoid the coupled-bunch instability. It is a three-cavity system: the accelerating cavity is coupled with a storage cavity via a coupling cavity.

This simulator calculates real-time evolution of base-band (I, Q-components) from difference formula of resonators. It is extended to three-cavity system by adding coupling terms in the equations. This calculation is performed by an FPGA. This simulator has I/Q modulators and demodulator, and then it can directly receive an RF signal as a cavity input, and can also output the responses as RF signals. Furthermore, this simulator can receive tuner control pulses, and simulate the cavity (de-) tuning. The cavity parameters such as Q-values and input coupling can be configured arbitrarily.

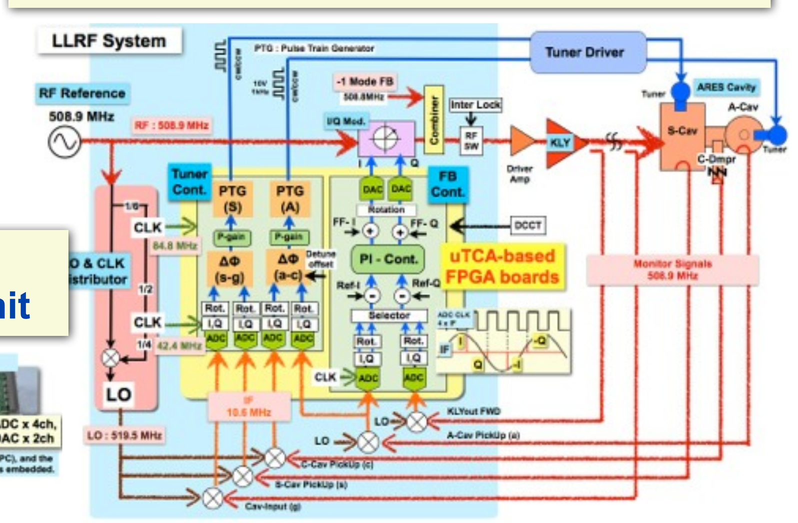
The stability condition of calculation will be is also discussed in this report.

Upgrade to SuperKEKB (SKB)

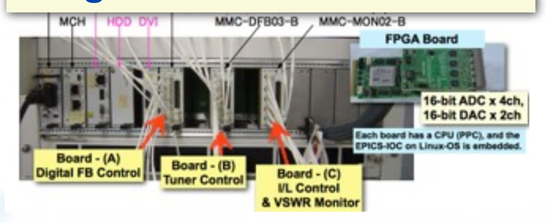
Luminosity: KEKB x 40 !
Beam Current : x 2
β_y @IP: x 20

New LLRF Control System for the SKB has been developed.

Block diagram of ARES cavity control

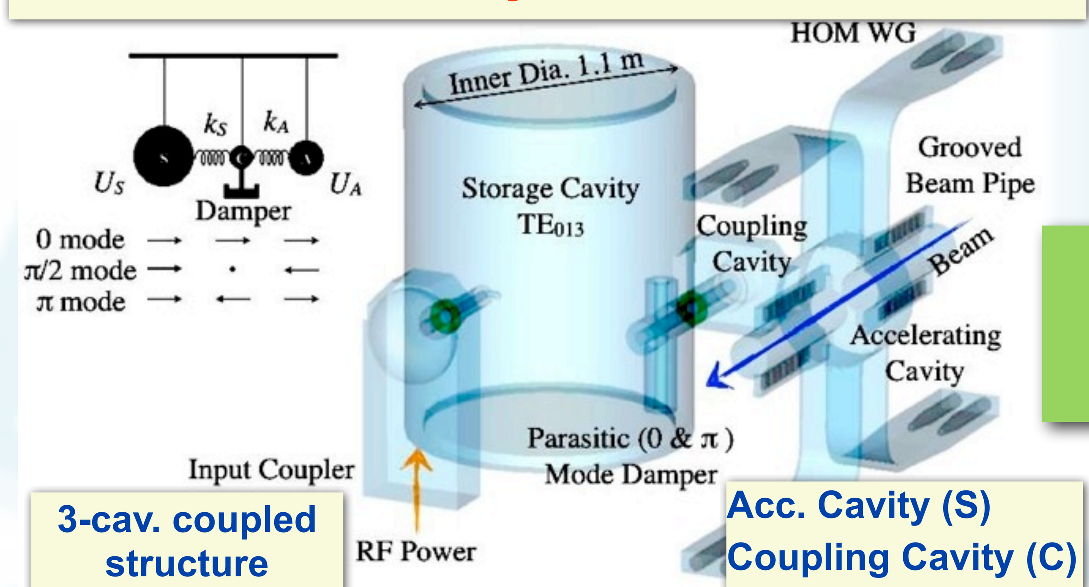


uTCA-platform Digital LLRF Control Unit



ARES Cavity Simulator has been developed for evaluation of the new LLRF control System

The ARES Cavity (C) T. Kageyama, et. al.



3-cav. coupled structure (π/2 mode)

Acc. Cavity (S)
Coupling Cavity (C)
Storage Cavity (A)

(C) T. Kageyama, et al., "The ARES cavity for KEKB", Proc. of APAC98, pp. 773-775 (1998)
http://accelconf.web.cern.ch/AccelConf/a98/APAC98/6D039.PDF

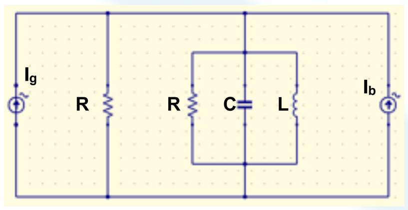
ARES Cavity Simulator

Tuner control pulses (rear panel)

Display of amplitude and phase of each cavity
RF Input (508.9MHz)
RF Output Reflection, A, C, S-cav.

Basic Algorithm (Single Resonator)

T. Schilcher, "Vector sum control of pulsed accelerating fields in Lorenz force detuned superconducting cavities", PhD. Thesis (1998)



Differential eq. of a resonator

$$\ddot{\mathbf{V}}(t)+\frac{\omega_0}{Q_L}\dot{V}(t)+\omega_0^2\mathbf{V}(t)=\frac{\omega_0 R_L}{Q_L}\dot{\mathbf{I}}(t)\qquad \omega_0=\frac{1}{\sqrt{LC}}\qquad R_L=\frac{R}{1+\beta}$$

Variable Separation into envelop and RF oscillation

$$\mathbf{V}(t)=\left[V_{cI}(t)+j\cdot V_{cQ}(t)\right]\cdot e^{-j\omega t}\qquad \mathbf{I}(t)=\left[I_{gI}(t)+j\cdot I_{gQ}(t)\right]\cdot e^{-j\omega t}$$

Cavity Diff. Eq. for the envelop

Neglect the 2nd-order time derivation $\ddot{V}=0$

Diff. Eq.

$$\begin{cases}\dot{V}_{cI}(t)+\omega_{1/2}V_{cI}(t)+\Delta\omega V_{cQ}(t)=R_L\omega_{1/2}I_{gI}(t)\\ \dot{V}_{cQ}(t)+\omega_{1/2}V_{cQ}(t)-\Delta\omega V_{cI}(t)=R_L\omega_{1/2}I_{gQ}(t)\end{cases}\qquad \omega_{1/2}=\frac{\omega_0}{2Q_L}\qquad \Delta\omega=\omega_0-\omega$$

Discrete Eq. of Envelop (like an IIR-filter)

Discrete formula

$$\begin{cases}V_{cI}^{n+1}=V_{cI}^{n}+\Delta t\cdot\omega_{1/2}\left(R_L I_{gI}^{n}-V_{cI}^{n}\right)-\Delta t\cdot\Delta\omega V_{cQ}^{n}\\ V_{cQ}^{n+1}=V_{cQ}^{n}+\Delta t\cdot\omega_{1/2}\left(R_L I_{gQ}^{n}-V_{cQ}^{n}\right)+\Delta t\cdot\Delta\omega V_{cI}^{n}\end{cases}$$

Input $R_L\mathbf{I}_g=2\sqrt{\beta}\mathbf{V}_g$

Reflection $\mathbf{V}_r=\mathbf{V}_c\sqrt{\beta}-\mathbf{V}_g$

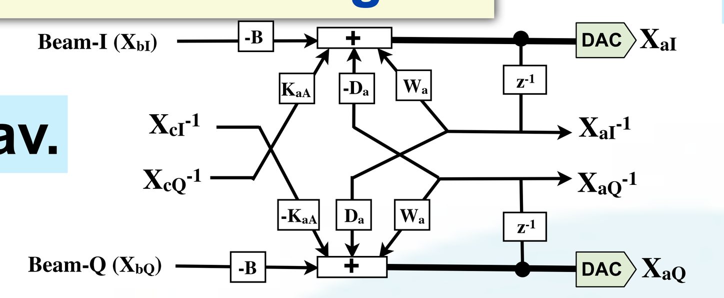
Extension to 3-Cav. System adding coupling terms

FPGA Function Diagram

ARES Cavity Model (3-reso. coupled model)

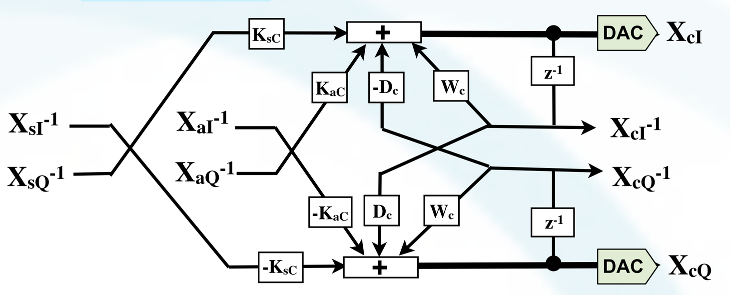
$$\begin{cases}\left[j\left(\frac{\omega}{\omega_a}-\frac{\omega_a}{\omega}\right)+\frac{1}{Q_a}\right]X_a=-j\frac{\omega}{\omega_a}\frac{1}{2}k_aX_c+\frac{R_a}{Q_a}I_b\\ \left[j\left(\frac{\omega}{\omega_c}-\frac{\omega_c}{\omega}\right)+\frac{1}{Q_c}\right]X_c=-j\frac{\omega}{\omega_c}\frac{1}{2}(k_aX_a+k_sX_s)\\ \left[j\left(\frac{\omega}{\omega_s}-\frac{\omega_s}{\omega}\right)+\frac{(\beta+1)}{Q_s}\right]X_s=-j\frac{\omega}{\omega_s}\frac{1}{2}k_sX_c+\frac{R_s}{Q_s}I_g\end{cases}$$

A-Cav.



A-Cav.
$$\begin{cases}X_{aI}=W_a\cdot X_{aI}^{-1}-D_a\cdot X_{aQ}^{-1}+K_{aA}\cdot X_{cQ}^{-1}-B\cdot X_{bI}\\ X_{aQ}=W_a\cdot X_{aQ}^{-1}+D_a\cdot X_{aI}^{-1}-K_{aA}\cdot X_{cI}^{-1}-B\cdot X_{bQ}\end{cases}$$

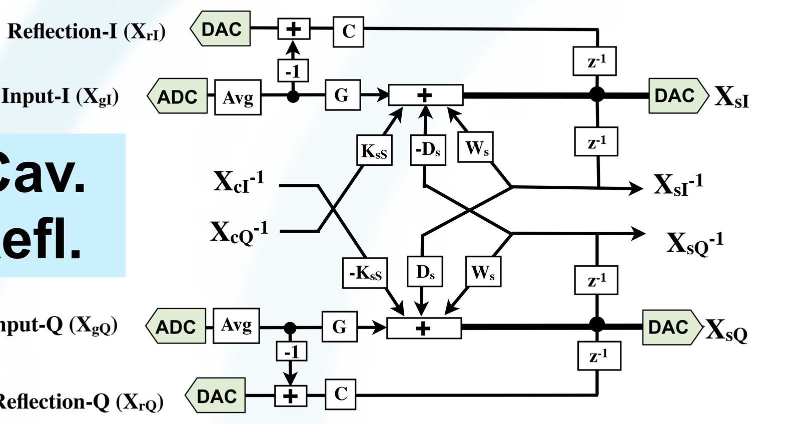
C-Cav.
$$\begin{cases}X_{cI}=W_c\cdot X_{cI}^{-1}-D_c\cdot X_{cQ}^{-1}+K_{aC}\cdot X_{aQ}^{-1}+K_{sC}\cdot X_{sQ}^{-1}\\ X_{cQ}=W_c\cdot X_{cQ}^{-1}+D_c\cdot X_{cI}^{-1}-K_{aC}\cdot X_{aI}^{-1}-K_{sC}\cdot X_{sI}^{-1}\end{cases}$$



Refl.
$$\begin{cases}X_{rI}=C\cdot X_{sI}^{-1}-X_{gI}\\ X_{rQ}=C\cdot X_{sQ}^{-1}-X_{gQ}\end{cases}$$

S-Cav.
$$\begin{cases}X_{sI}=W_s\cdot X_{sI}^{-1}-D_s\cdot X_{sQ}^{-1}+K_{sS}\cdot X_{cQ}^{-1}+G\cdot X_{gI}\\ X_{sQ}=W_s\cdot X_{sQ}^{-1}+D_s\cdot X_{sI}^{-1}-K_{sS}\cdot X_{cI}^{-1}+G\cdot X_{gQ}\end{cases}$$

S-Cav. &Refl.



$$\Delta t=\frac{1}{f_{clock}}\qquad \omega_{\mu/2}=\frac{\omega_\mu}{2Q_\mu}\qquad \Delta\omega_\mu=\omega_\mu-\omega\qquad \mu: s, c, a$$

$$C=\sqrt{\beta}\qquad G=2\sqrt{\beta}\cdot\Delta t\cdot\omega_{s/2}\qquad D_\mu=\Delta t\cdot\Delta\omega_\mu\qquad B=\Delta t\cdot\omega_{a/2}$$

$$W_{a,c}=1-\Delta t\cdot\omega_{a,c/2}\qquad W_s=1-(\beta+1)\cdot\Delta t\cdot\omega_{s/2}$$

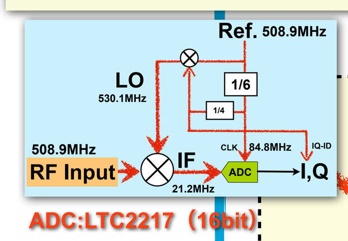
$$K_{\mu v}=\frac{k_\mu}{2}\cdot\Delta t\cdot\omega_{v/2}\cdot Q_v=\frac{k_\mu\cdot\Delta t\cdot\omega_\mu}{4}$$

Translated into 24bit-integer calculation (fixed point algorithm) for FPGA

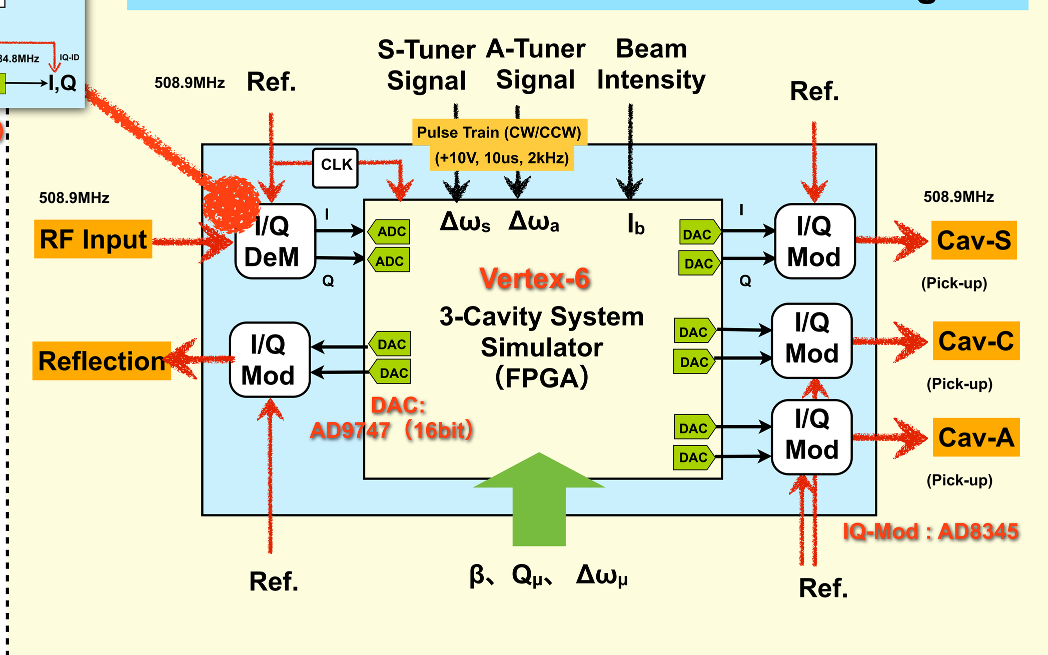
D_μ ($\Delta\omega$) is increased/decreased by receiving tuner-control pulses (CW/CCW). Changing rate of D_μ for one pulse is variable arbitrarily.

Function and Feature of ARES Simulator

IQ-Sampling of IF Signal



Schematic draw of the functional block diagram



(1) Time-evolutionary simulation of baseband (I,Q-components) by FPGA.
(2) Extended to 3-cavity coupled system (π/2 mode operation).
(3) Direct RF signal (509MHz) input & output.
(4) Cavity reflection signal is simulated as real time response.
(5) Tuner control (tuning/detuning) can be also simulated with pulse train signal input.
(6) Beam loading effect can be included.
(7) Cavity parameters is variable arbitrarily.
(8) Bench-top use or rack mounting

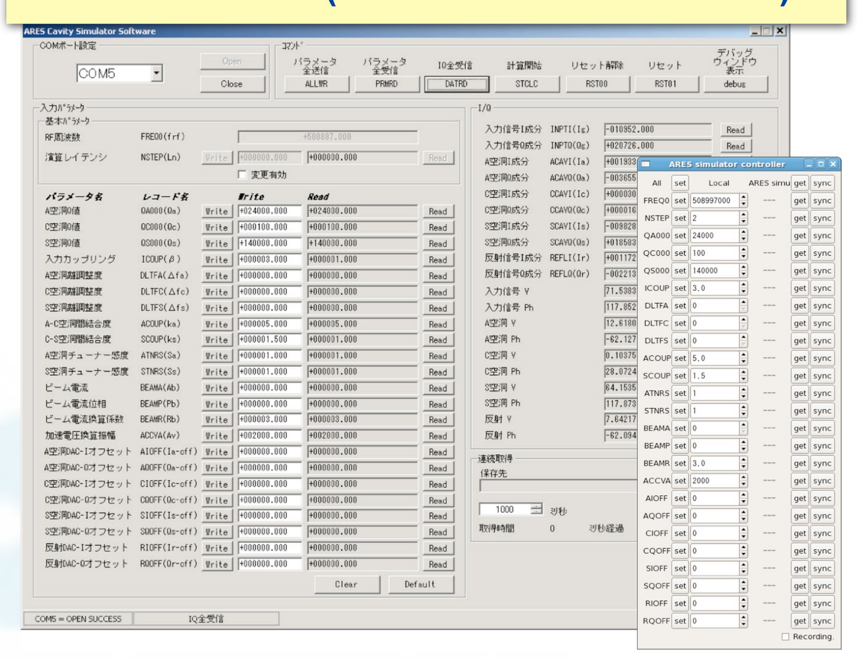
ARES Cavity Parameters

Coupling : β	3
Q_0 of Accelerating Cavity : Q_a	26000
Q_0 of Coupling Cavity : Q_c	100
Q_0 of Storage Cavity : Q_s	140000
Coupling between A & C : k_a	5%
Coupling between C & C : k_s	1.5%
Wall Loss Power : P_c	150kW = (A) 60kW+ (S) 90kW
Accelerating Gradient	0.5 MV (P_c = 150kW)
Synchronous Phase : φ_s	about 80 deg.

Effective (Total) Value of ARES

Q_{tot}=110000 β_{eff}=2.7

User Interface (USB connection with PC)



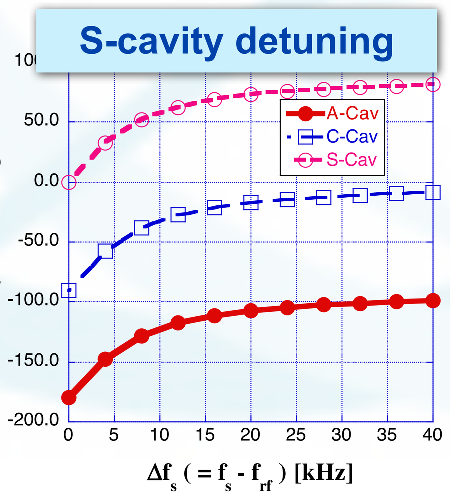
Performance Confirmation

Detuning Property (Phase Change)

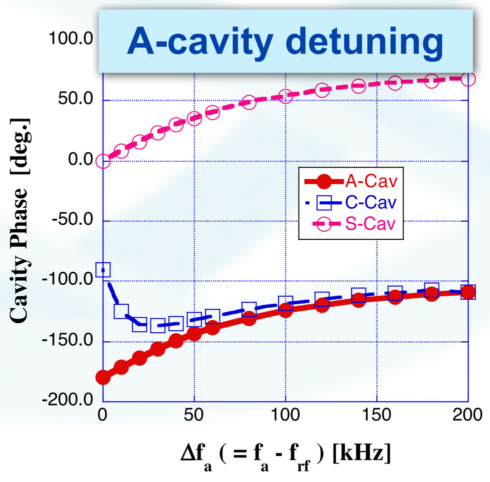
Phase change due to the cavity detuning was measured. Right plots show cavity phase v.s. detuning.

These results represent well typical property of the ARES.

S-cavity detuning



A-cavity detuning



Stability Condition of Calculation

Following condition should be satisfied for the calculation stability.

$v_g\Delta t<\sqrt{2}$ from analogy of FDTD analysis : $v\cdot\Delta t<\sqrt{(\Delta x)^2+(\Delta y)^2+(\Delta z)^2}=\delta\sqrt{3}$

v_g: group velocity of π/2 mode

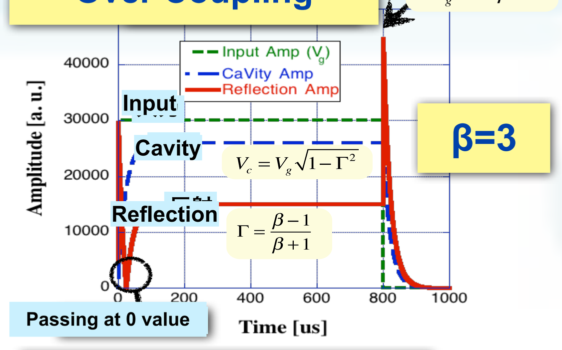
$$v_g=\frac{d\omega}{d\phi}=\frac{\pi f_{rf}\sqrt{k_a^2+k_s^2}}{2}$$
[cavity-cell /s]

$$\sqrt{k_a^2+k_s^2}<\frac{2\sqrt{2}}{\pi f_{rf}\Delta t}\quad \text{or}\quad \Delta t<\frac{1}{\pi f_{rf}}\frac{2\sqrt{2}}{\sqrt{k_a^2+k_s^2}}$$

Transient Response of Pulse-Modulated RF Input

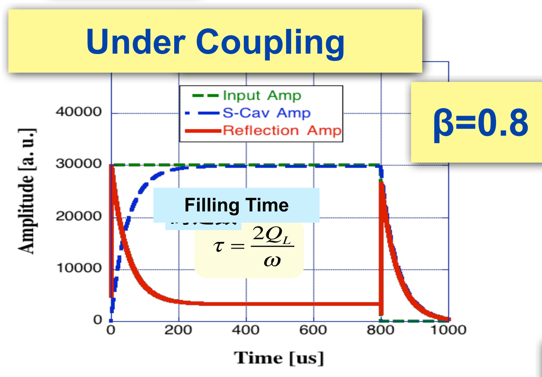
Envelop of RF response of a cavity for pulsed incident (Analytical calculation)

Over Coupling $\frac{V_{c\_end}}{V_i}=\frac{2\beta}{\beta+1}$



β=3

Under Coupling

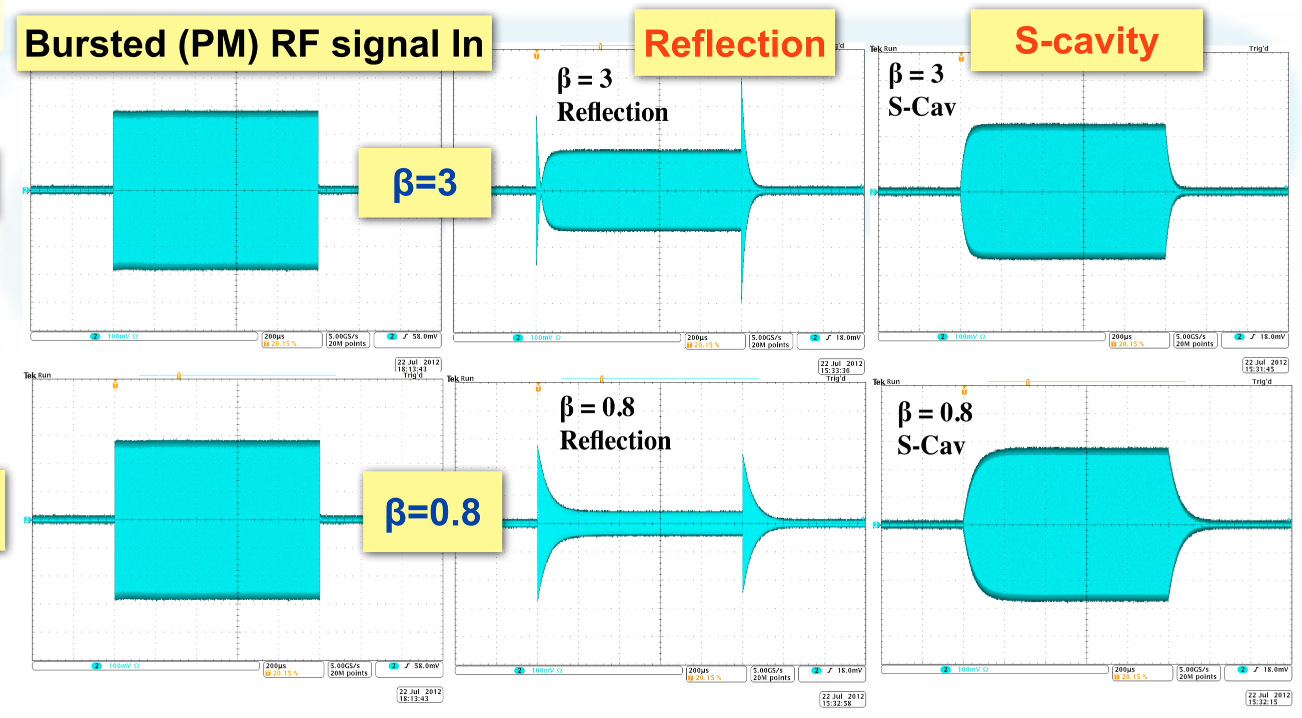


β=0.8

ARES cavity simulator outputs (RF signals)

RF signals of the response observed by an oscilloscope@5GS/s

Bursted (PM) RF signal In | Reflection | S-cavity



Transient response of this simulator agrees well with prediction of analytical calculation (left side plot), where $Q_L=Q_{tot}/(1+\beta_{eff}=2.7)$